JPL

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Long Baseline Optical Interferometry and the Search for Exo-Planets

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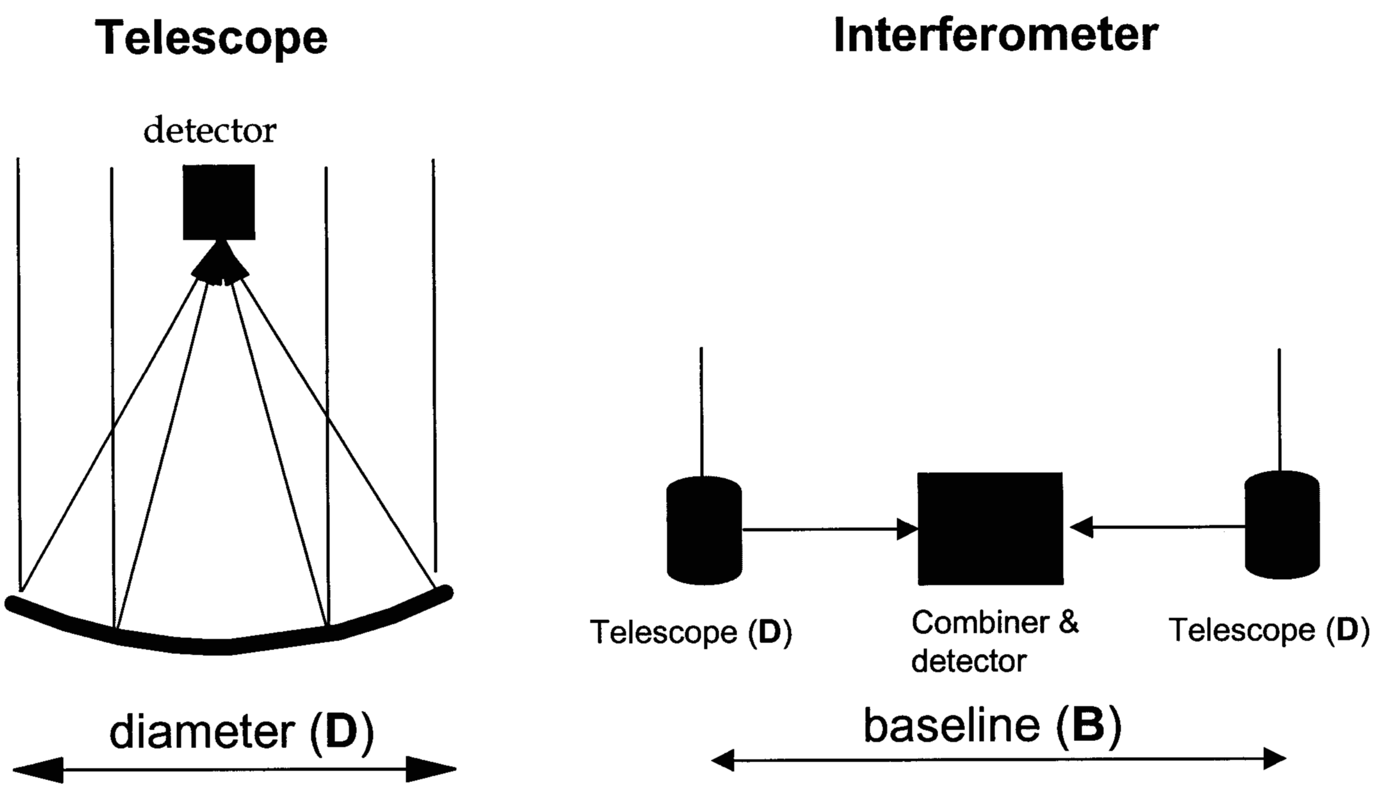
Stellar Interferometry

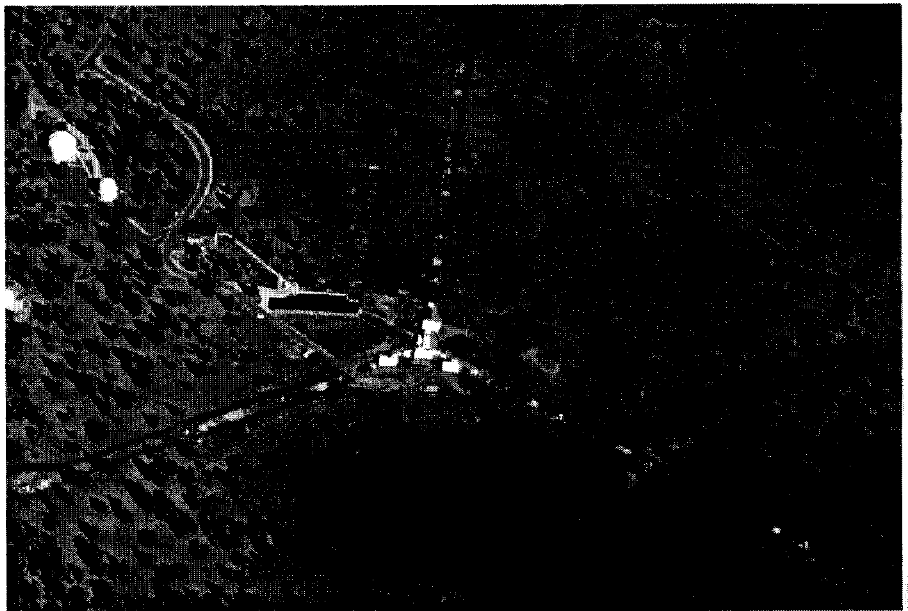
- What is it, why do it?
  - Introduction to Stellar Interferometry
- The search for planets outside our solar system
  - Historical perspective, discoveries in the last ~4 years
- Interferometry and Planets
  - Major approaches for exo-planet detection
- Projects and Missions, technologies under development
  - *Keck Interferometer*
  - *Space Interferometry Mission*
  - Space Technology 3
  - Terrestrial Planet Finder (TPF)

What is an Optical Interferometer?

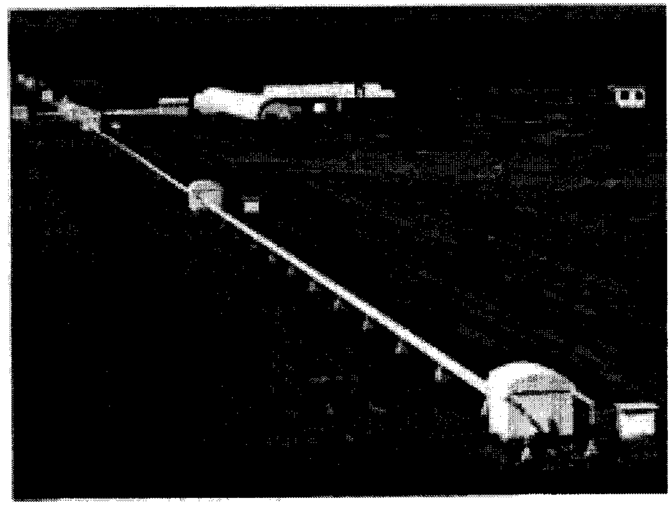
- An interferometer combines the light from several small telescopes to yield the angular resolution of a much larger telescope



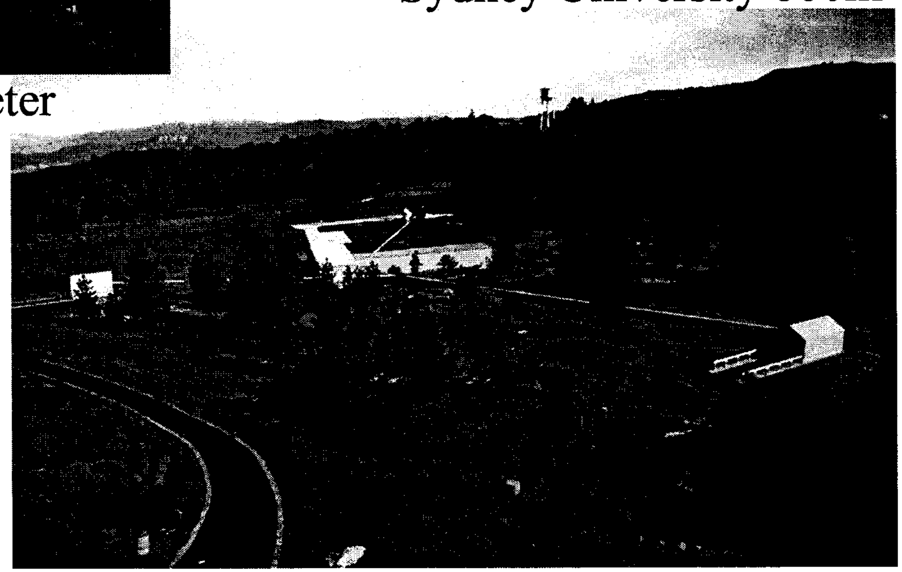
Ground Optical Interferometers



Navy Prototype Optical Interferometer
460m baseline



Sydney University 600m



Palomar Interferometer
110 m

Why Interferometry?

1 - Imaging resolution

λ/**B** for an interferometer vs. λ/**D** for a telescope

B, separation of apertures, can cost-effectively be made very large

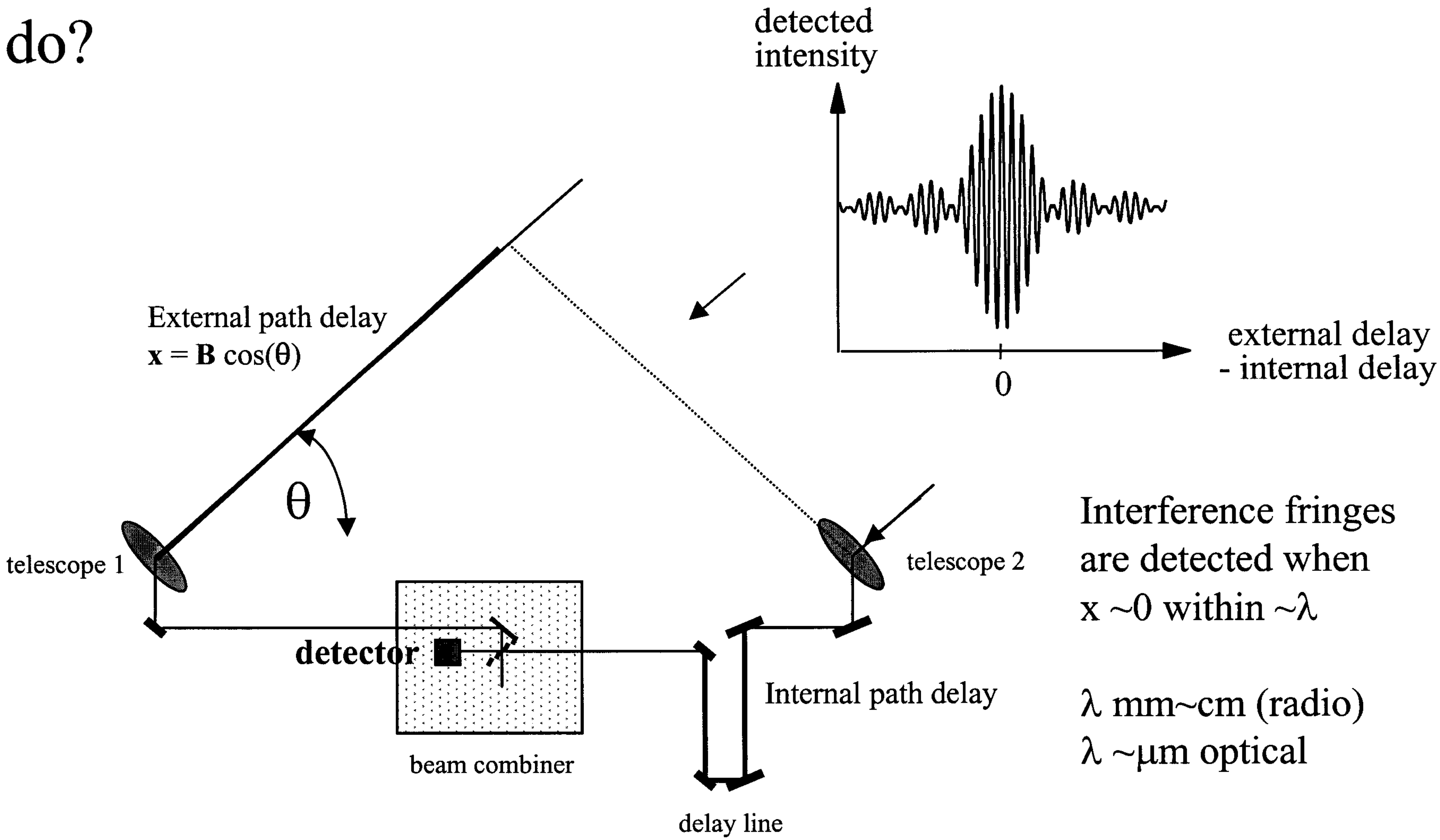
2 - Astrometric Accuracy

Interferometers have a simple geometry which can be accurately monitored to minimize systematic errors

Interferometers use starlight efficiently

3 - Nulling, interferometers have the ability to "null starlight" with extreme precision, in order to see the presence of planets or other dim objects orbiting a star

What does a stellar interferometer do?



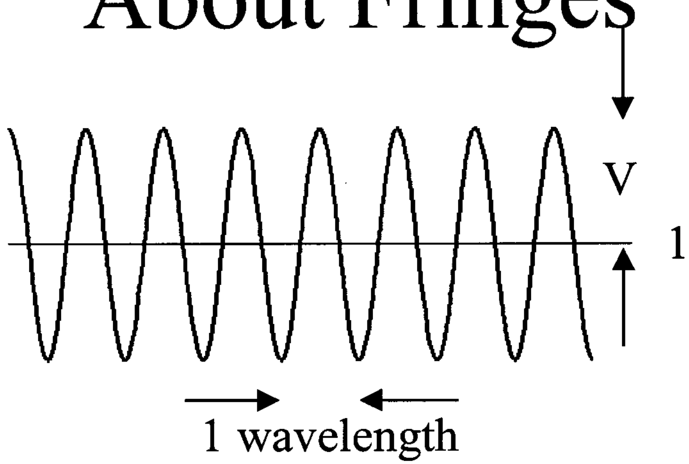
Interference fringes are detected when $x \sim 0$ within $\sim\lambda$

λ mm~cm (radio)
λ ~μm optical

The peak of the interference pattern occurs when the internal path delay equals the external path delay

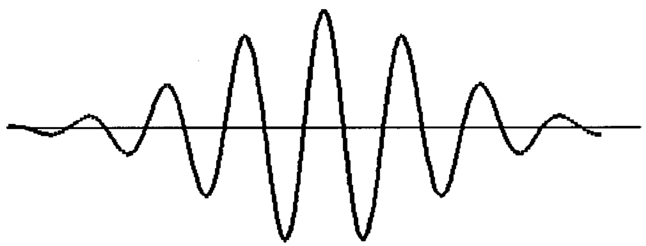
About Fringes

Narrowband (laser) fringe
$\Delta\lambda \sim 0$



-Fringes at all delays

Wideband (white light) fringe
$\Delta\lambda >> 0$

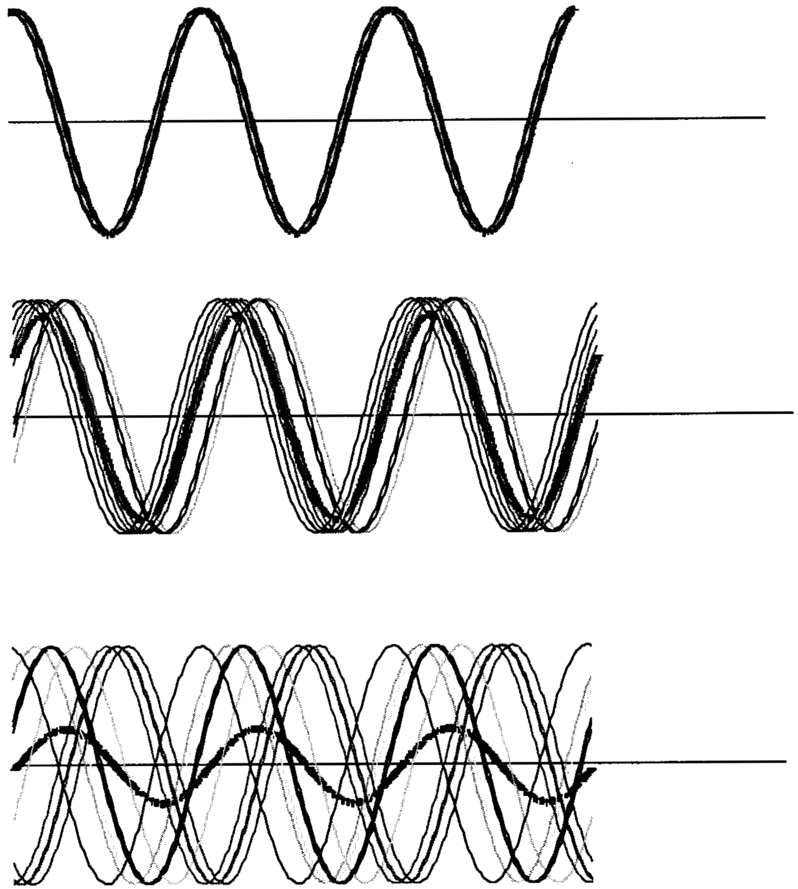


-Number of fringes ~ $\Delta\lambda/\lambda$
-There is a well defined central fringe

-Fringe position tells us about position of source
-Fringe visibility tells us about structure of source
(extended sources have reduced fringe visibility)

Requirements on Fringe Stabilization

Vibrations blur out the fringe

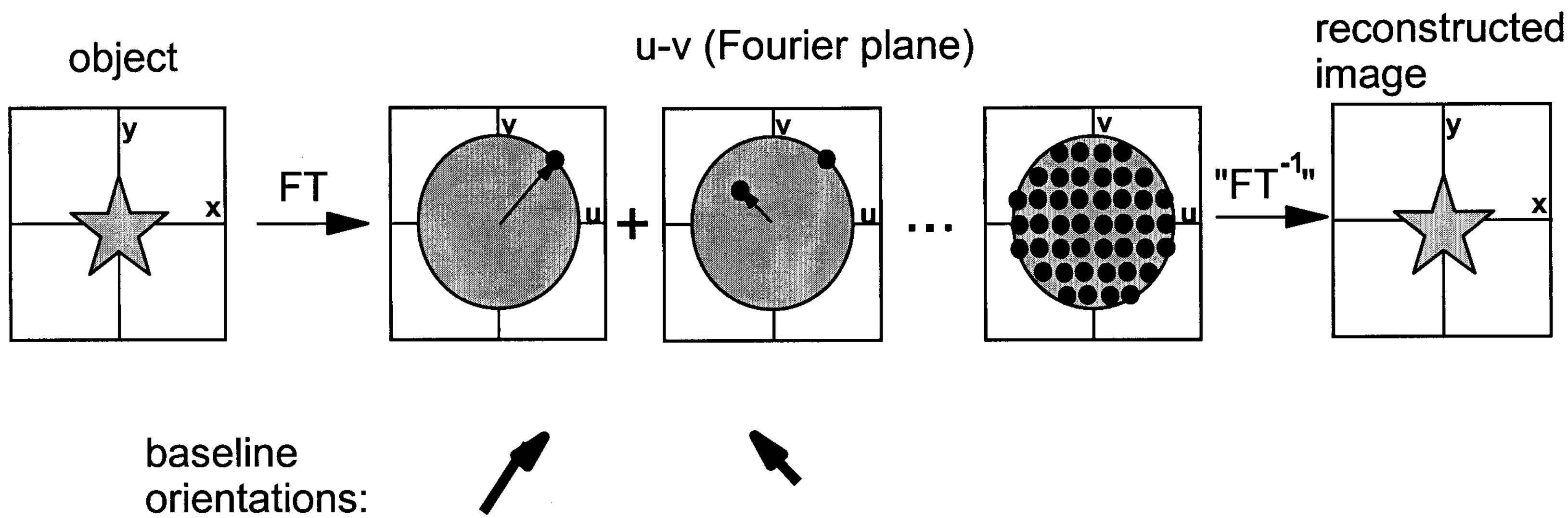


Fringe Visibility
(contrast)

Fringe Position
(or phase)

Need real-time control of pathlength to ~10 nm ($\lambda/50$) for high fringe visibility

Imaging with an Interferometer

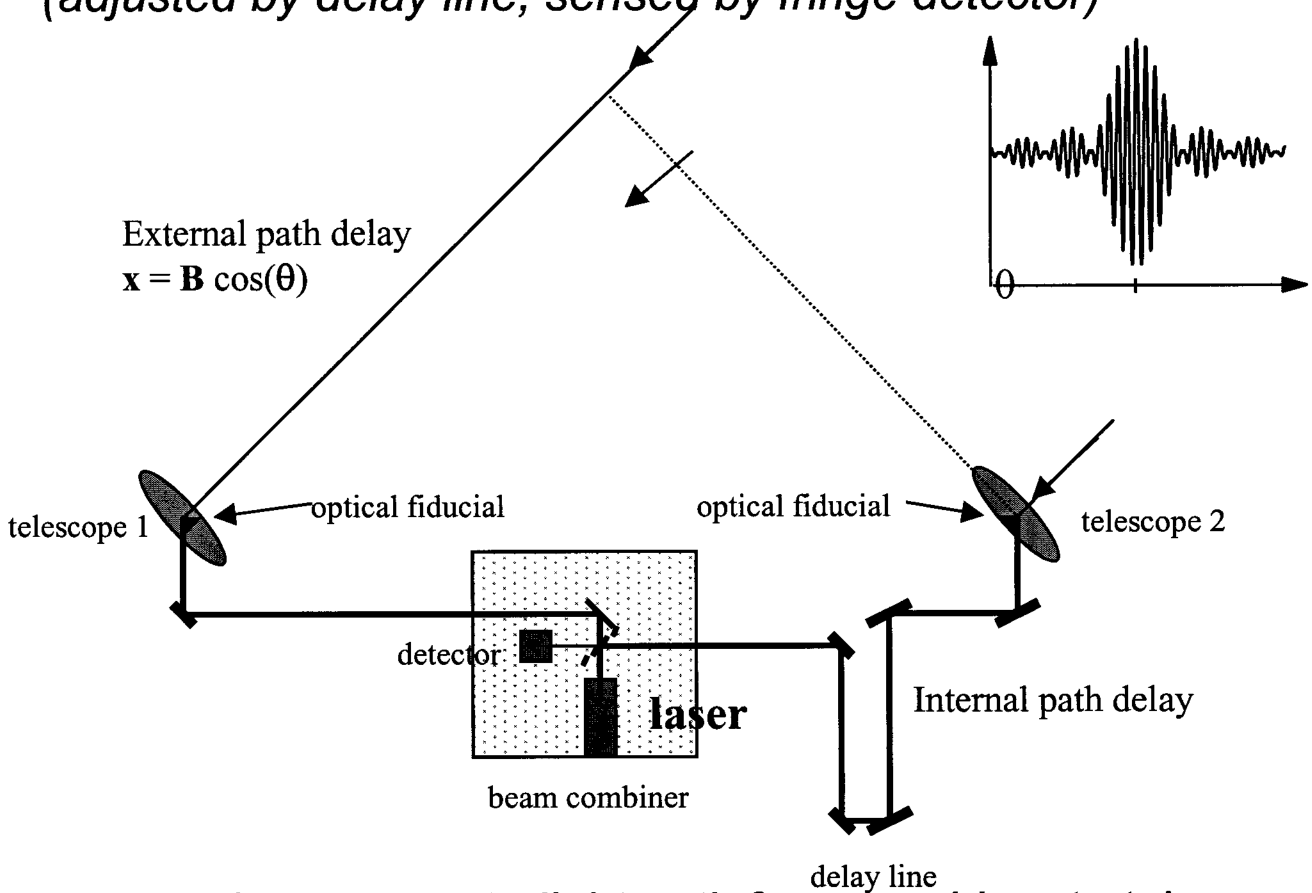


- The interferometer measures the Fourier transform of the object
- Each baseline orientation selects one point in the (u,v) plane
  - The data for this point is the fringe visibility and phase
- With many baseline orientations, you fill in the (u,v) plane
- The image is reconstructed from these Fourier-domain measurements

Astrometry, the Position/Motion of Stars

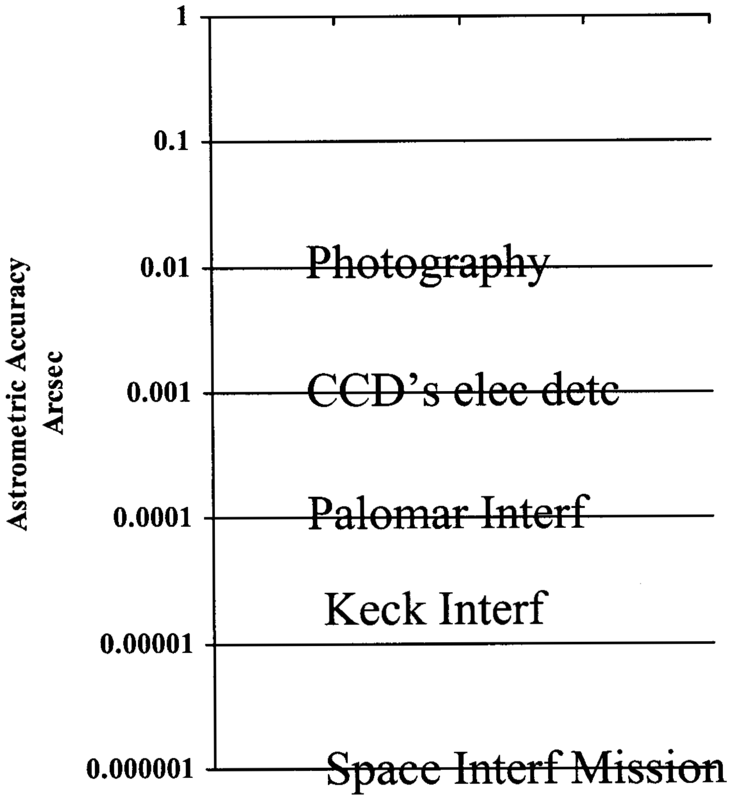
Laser gauge measures internal delay

(adjusted by delay line, sensed by fringe detector)



Laser path retraces starlight path from combiner to telescopes

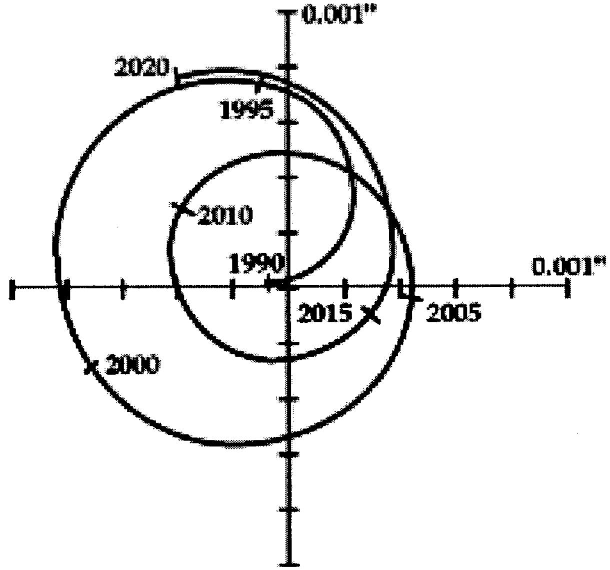
Astrometric Accuracy



- Traditional astronomical telescopes can measure the position of a star relative to nearby background stars ~1 milliarcsec (mas)
- The next generation of Stellar interferometers hope to improve on that by 10, 100 and eventually a factor of ~1000

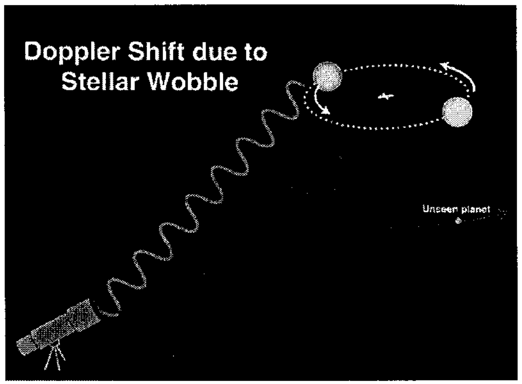
Search for Planets Orbiting Other Stars

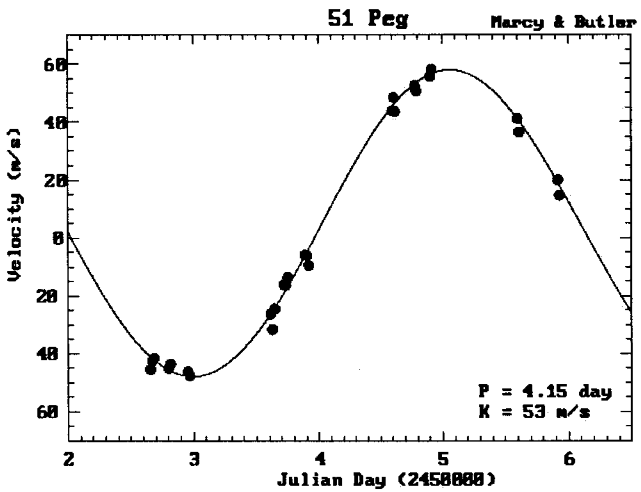
- Humans have been curious about the possibility planets around other stars for hundreds of years.
- In the middle this century, the favored technique was astrometry, looking for the sideways wobble of a star due to the gravitation pull of the planet
- At that time, astronomers using Photographic techniques thought they had found a Jupiter sized planet around Barnard's star. This discover turned out to be false.
- It wasn't until 1996 that a real planet was discovered, and not by astrometry.



Motion of the Sun from 10pc away

51 Peg, the First Extra-Solar Planet

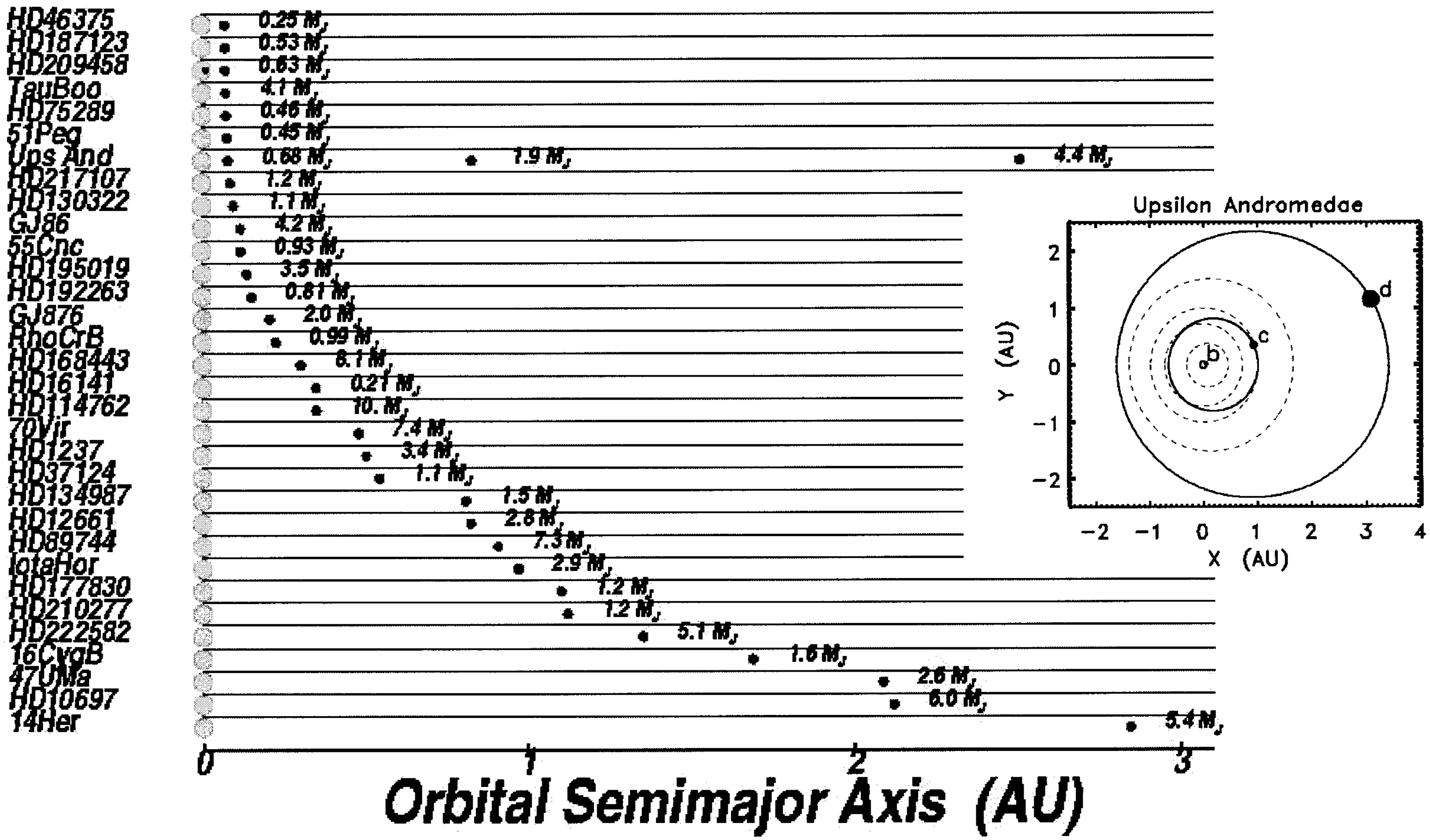




- Discovered by Michel Mayor and Didier Queloz, Oct 1996, confirmed by G. Marcy and P. Butler
  - mass > 0.44 Jupiter
  - Period 4.2 days
  - Distance from star 0.051 AU
- Since then the doppler technique has discovered ~35 planets around nearby stars.
- These planets are very different the ones in our own solar system

Known Planets around Nearby Stars

Planets found using
radial velocity techniques



Properties of Known Planets

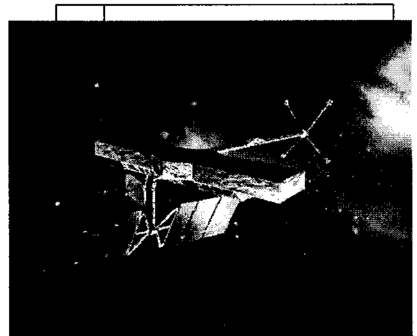
- ~Jupiter mass objects
- Many in close (<0.2AU) orbits around the parent star
- Eccentric Orbits (elliptical, not circular orbits)
- What are the properties of planets in our solar system?
  - Jupiter mass Gas Giants far from the Sun (5~40 AU)
  - Rocky planets (Earth, Mars, Venus, Mercury) near the Sun
  - Circular, coplanar orbits
- What happened to Astrometric detection of planets?

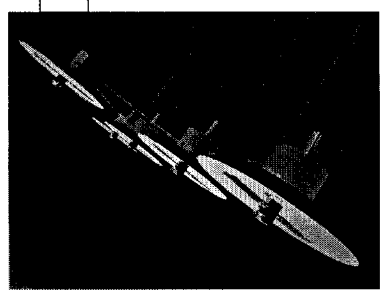
Interferometry and Planet Detection

- There are several techniques for detecting planets around nearby stars.
  - Indirect - Doppler/radial velocity of the star
    - High resolution spectragraphs on large telescopes
  - Indirect - Astrometry (transverse wobble) of the star
    - Long baseline interferometer on the ground and in space
  - Direct - IR, look for the IR emission of the planet
    - "hot jupiters" from large ground based interferometers
    - Earths with large cyrogenic interferometers in space

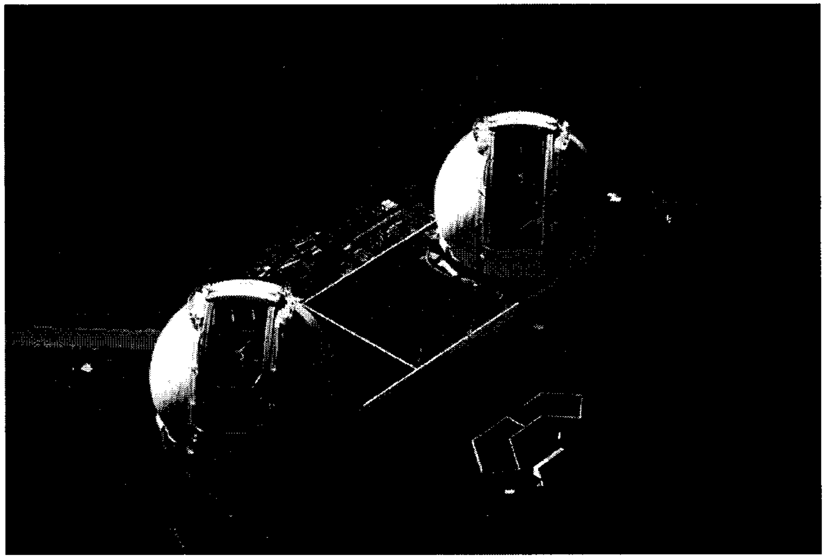
The Next 2~12 Years

- Keck Interferometer
  - Astrometric Planet detection ~20uas
  - Hot Jupiter direct detection
  - Dust around nearby stars
- Space Interferometer Mission SIM
  - Astrometry ~1uas (~3 Earthmass)
  - Demonstrate Nulling in space
- Terrestrial Planet Finder TPF
  - Direct detection of Earth-like planets
  - Low resolution spectra of atmosphere

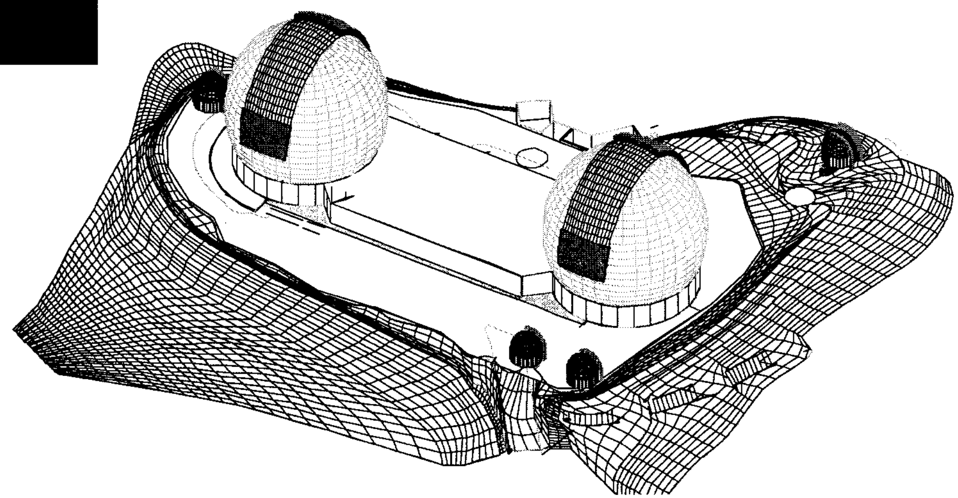




Keck Interferometer



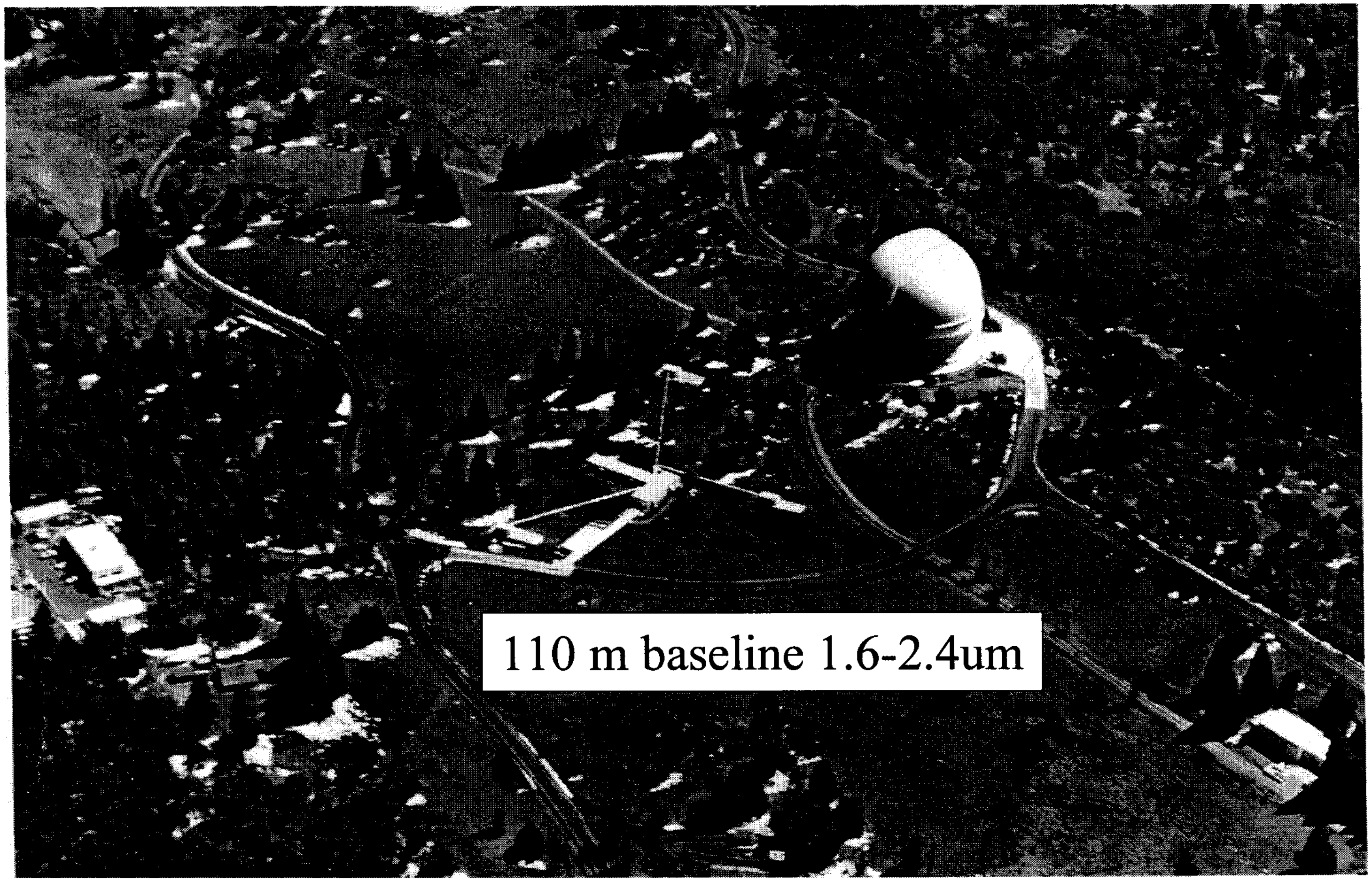
Keck Observatory (Caltech/U.C.)
Twin 10m telescopes on Mauna Kea



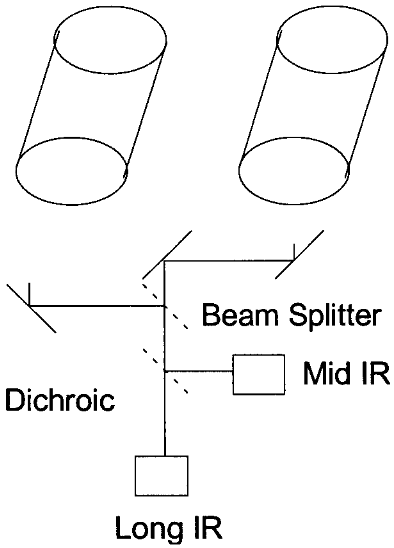
Keck Interferometer is
an addition to the Observatory
that adds 4 1.8m "outriggers"
and a beam combining facility
so that all 6 elements of the
array can operate as a single
Telescope ~100 m across.

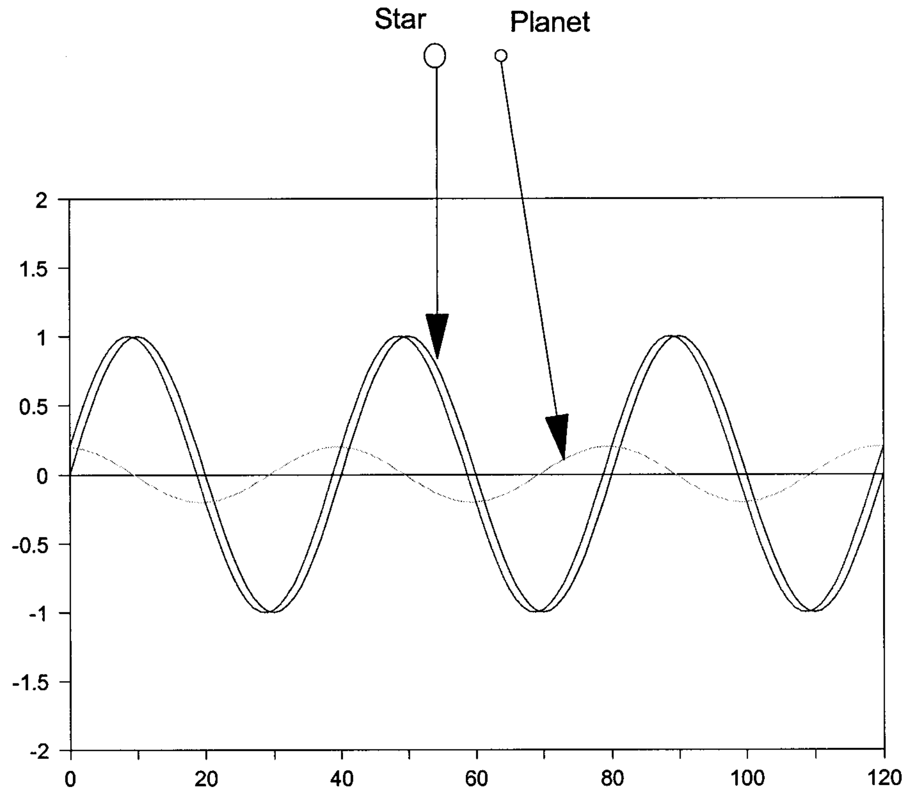
Palomar Testbed Interferometer

Technology Prototype for Keck Interferometer



Direct Detection of Hot Jupiters

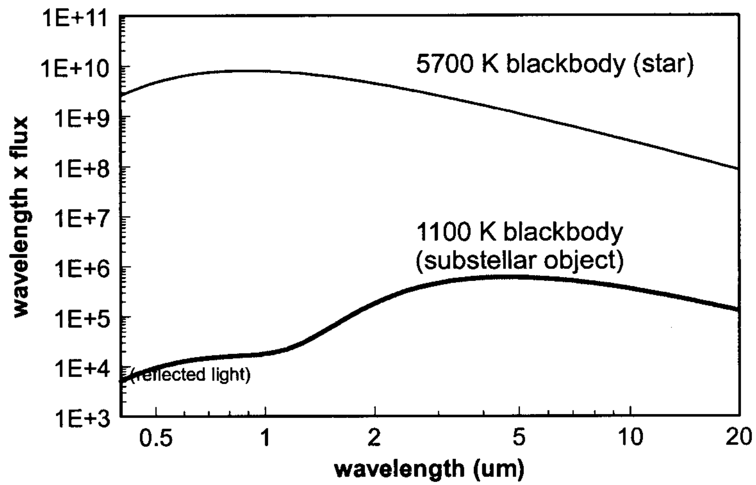


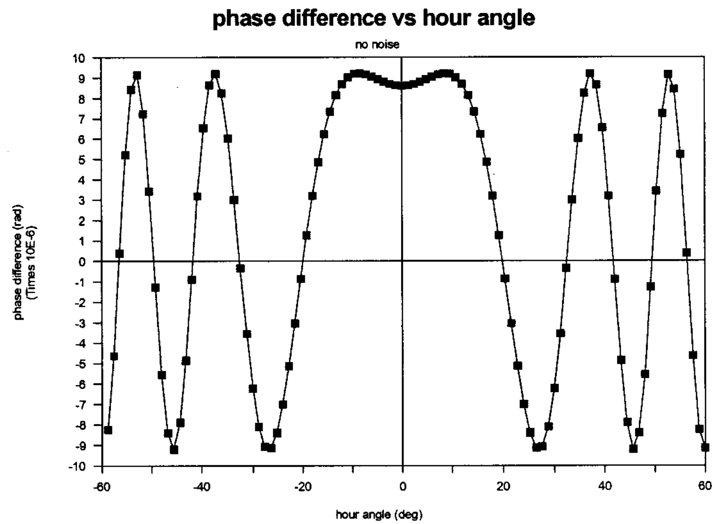


Phase Difference Interferometry for Planet Detection

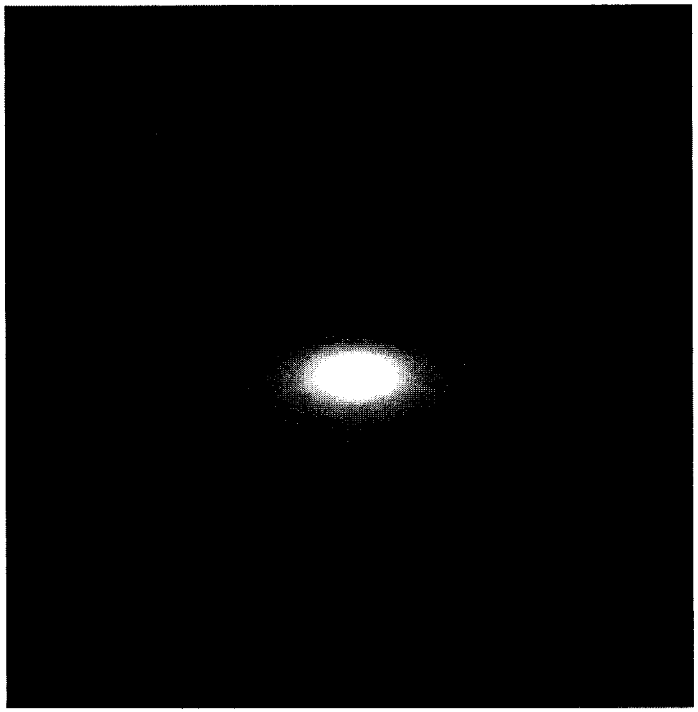
Direct Detection of Hot Jupiters

- Problem is not SNR - need to control systematic errors
- Use two-color phase referencing
  - Use object observed at a short wavelength as phase reference
    - Center of light will be close to star
  - Observe object at a longer wavelength for science measurement
    - Center of light will be displaced toward planet
  - Phase difference is observable
    - Very insensitive to systematics
- Observations of GL229B showed that significant changes in the flux ratio may be present just within the 1.6 and 2.2 um bands.



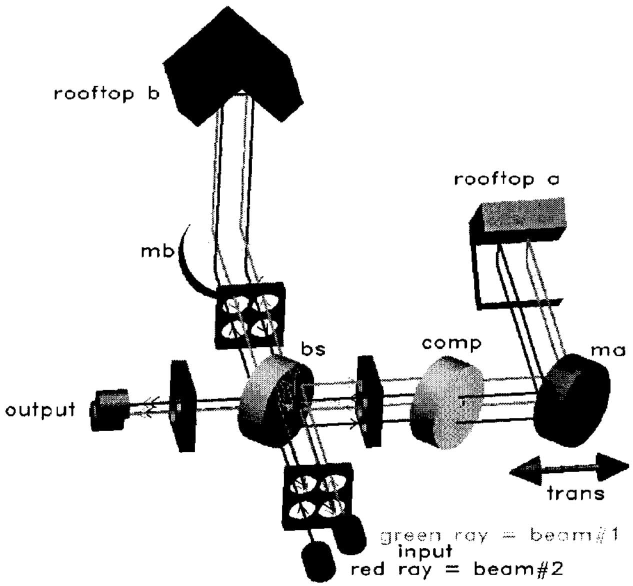


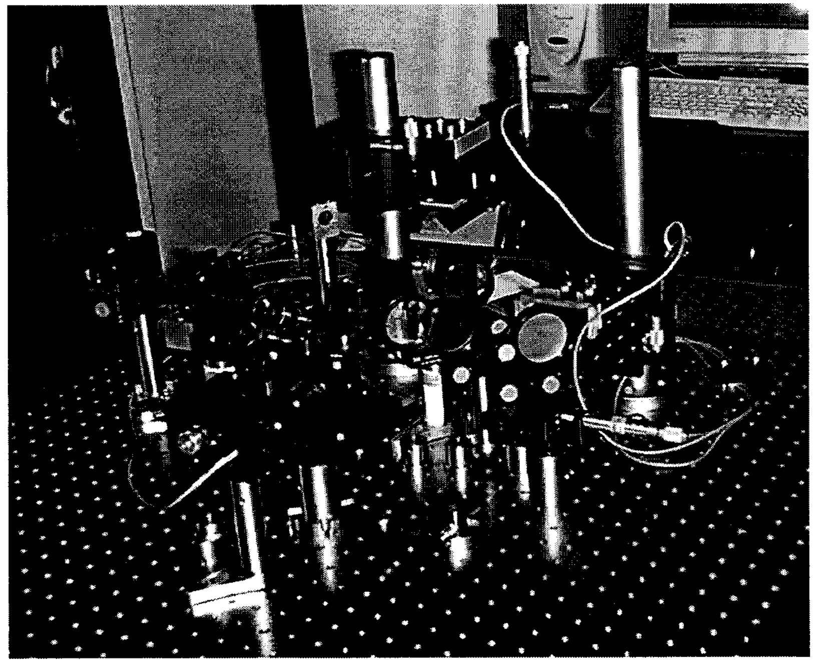
Exo-Zodi

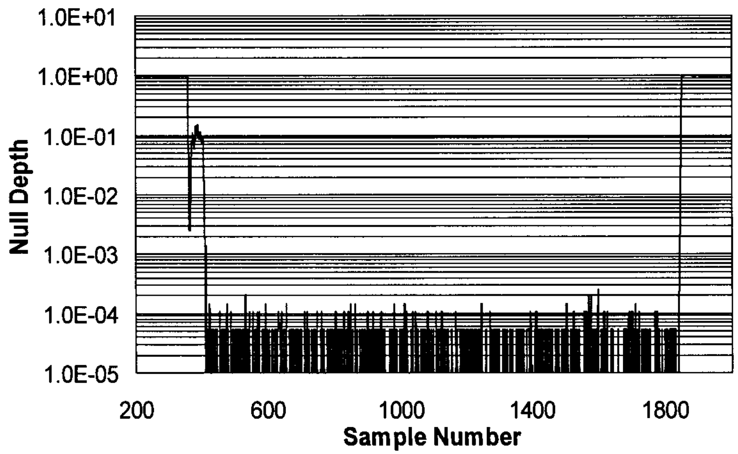


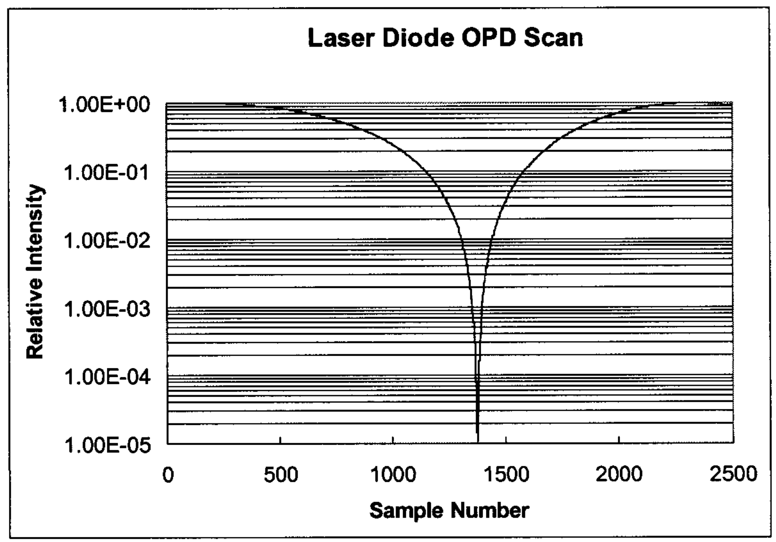
- NASA is very interested in finding Earth like planets around nearby stars
- There is one unavoidable source of astrophysical "noise", the disk of dust around the target star.
- For our own solar system, the dust in the inner solar system will emit more 10um radiation than an Earth (~50).
- To properly plan the TPF mission NASA needs to survey a number of nearby stars for the level of exo-zodi dust.

Nulling Interferometers

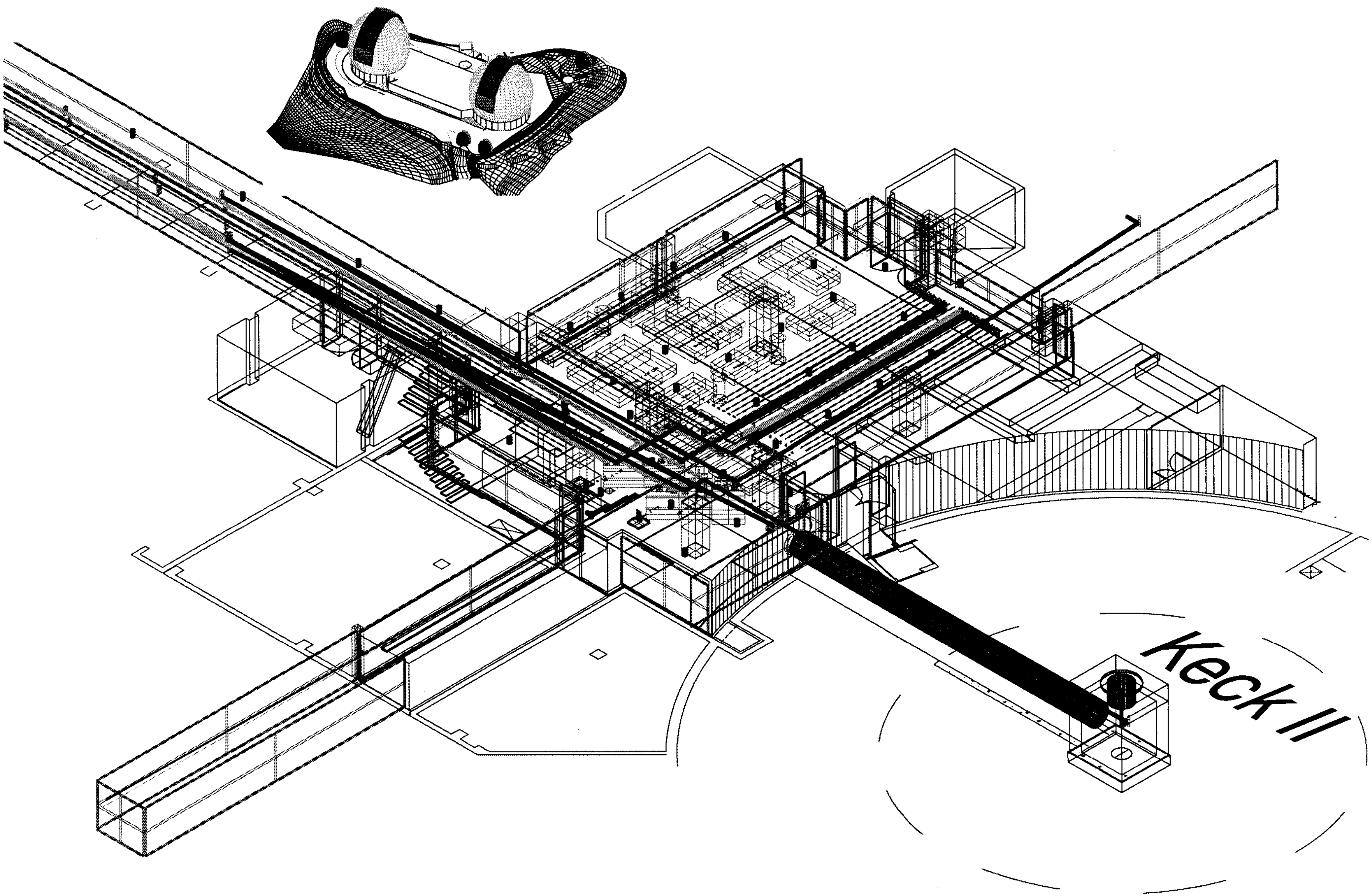




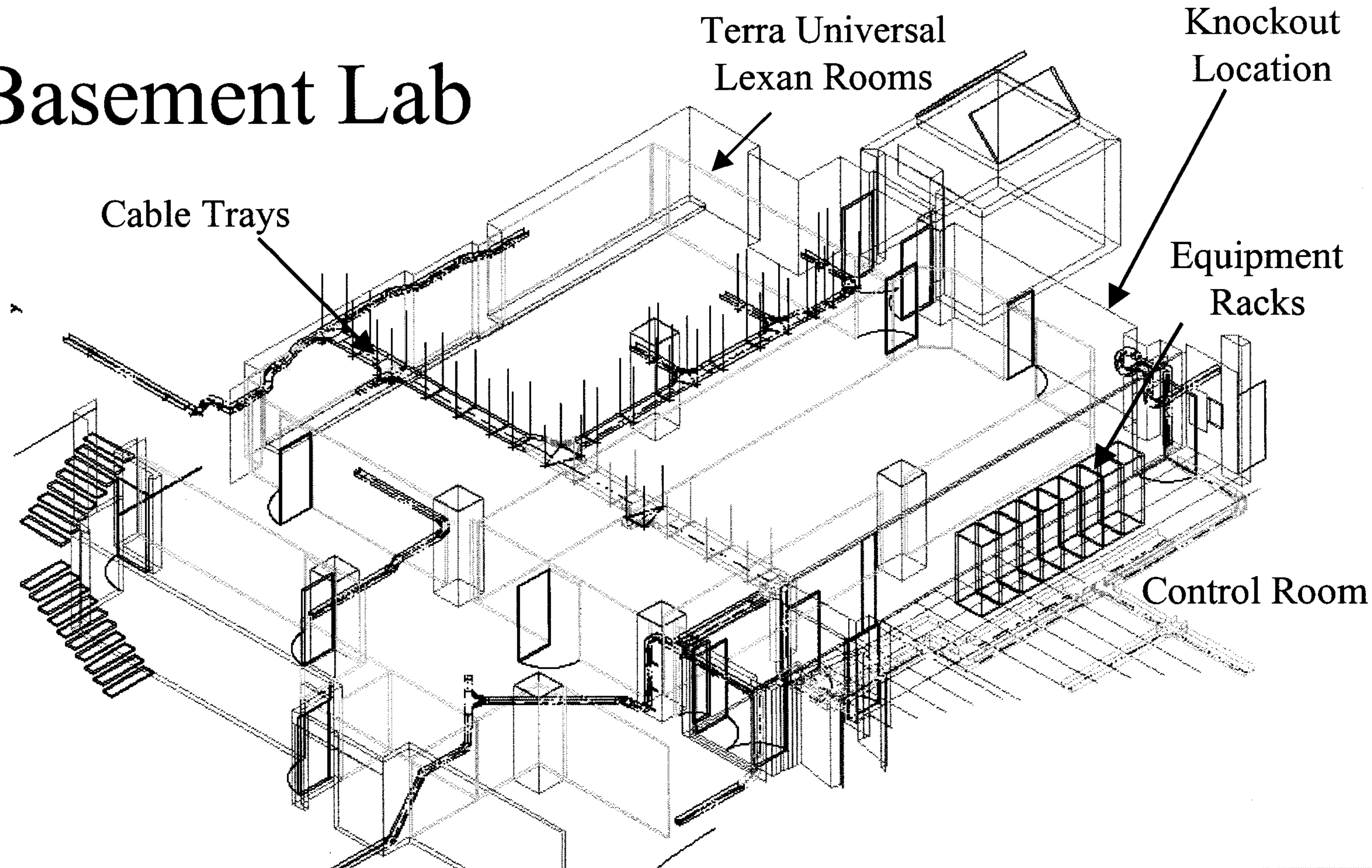


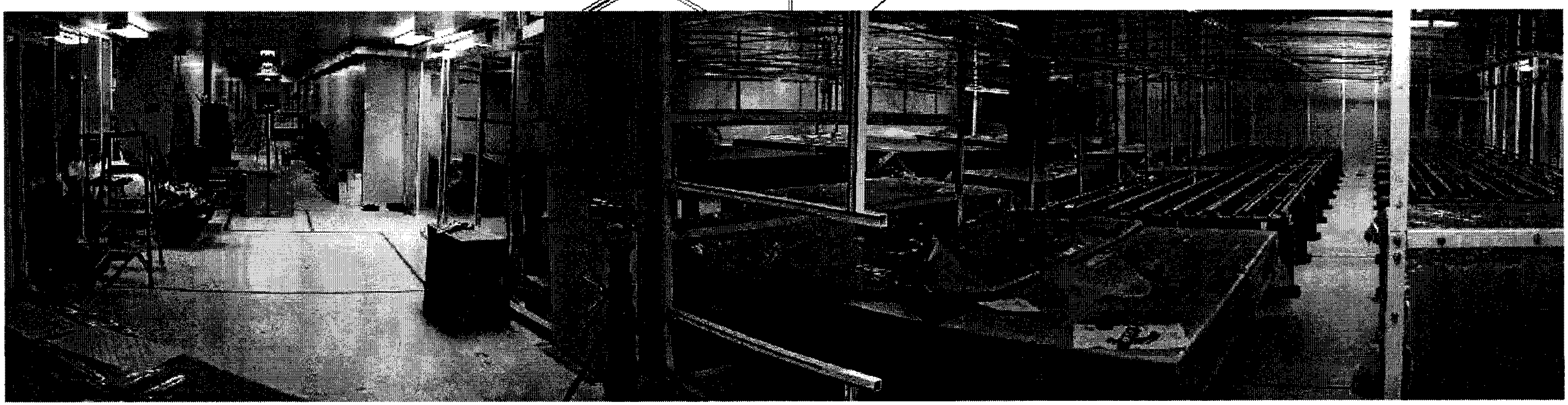


Basement Keck Interferometer

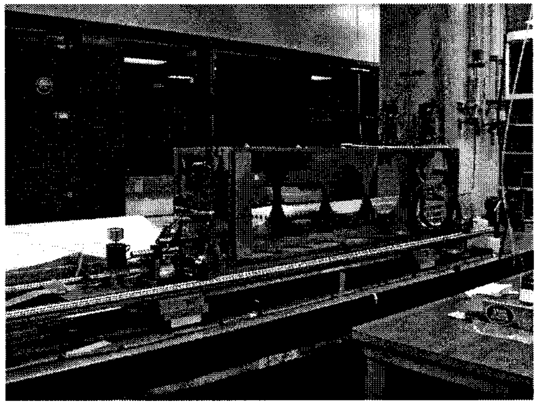


Basement Lab

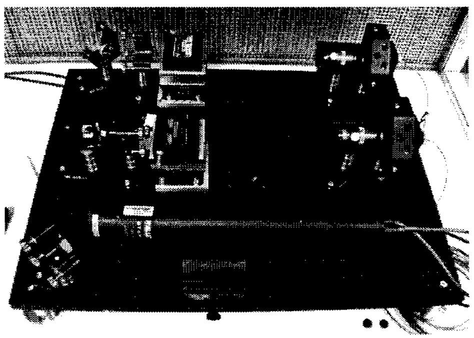




Component Hardware

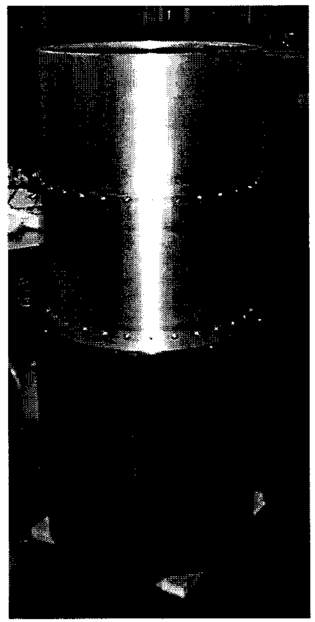


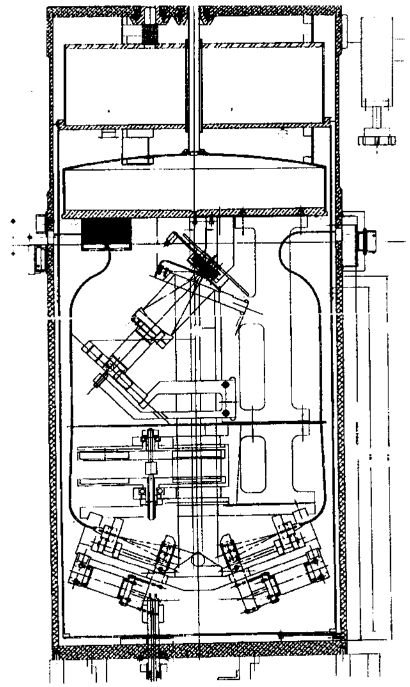
Fast delay lines



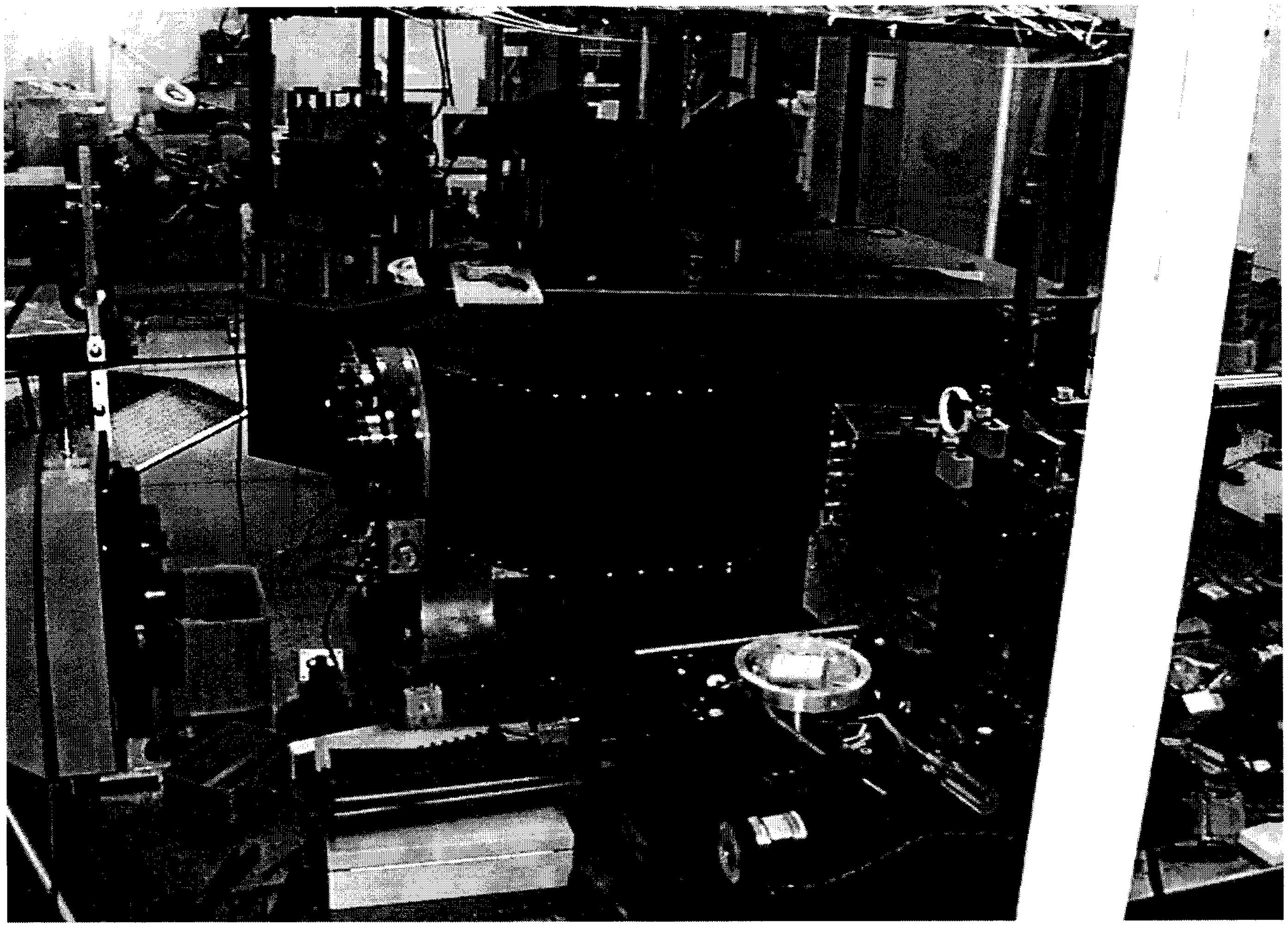
Laser metrology

Dewar and camera

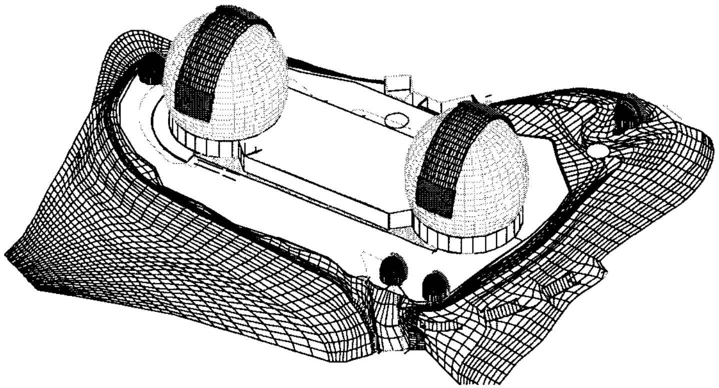


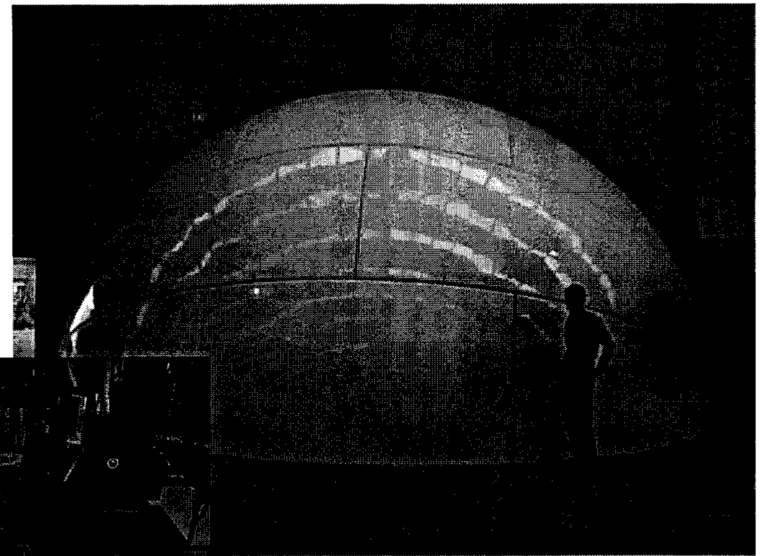


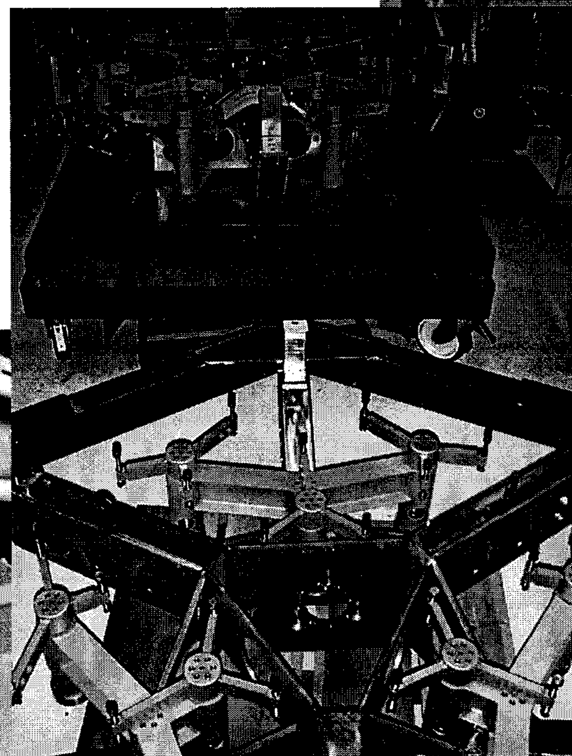
K1 Adaptive Optics

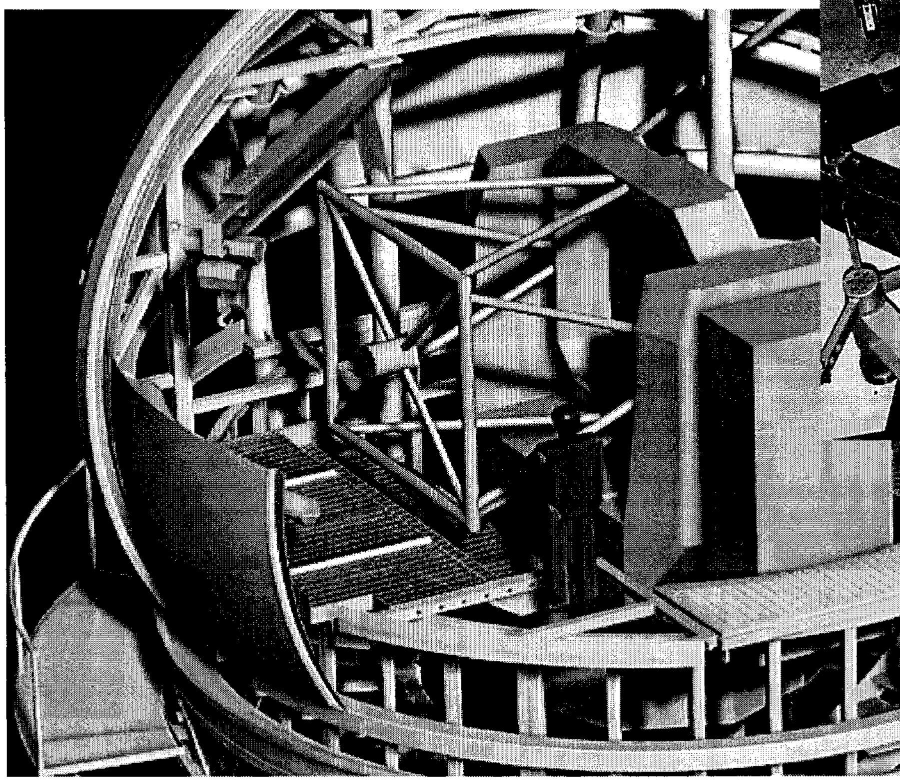


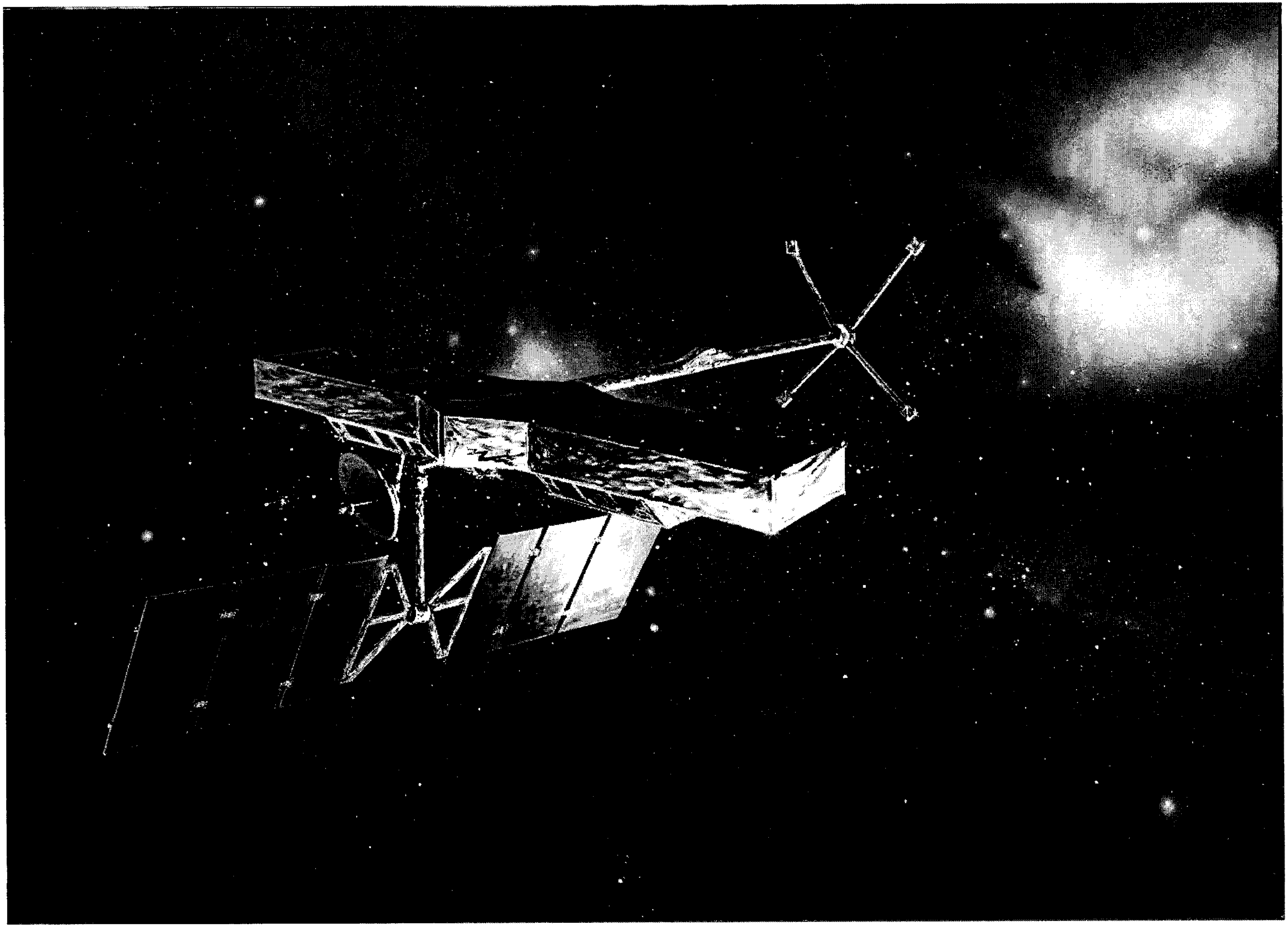
Outrigger 1.8m Telescopes





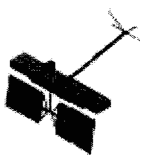




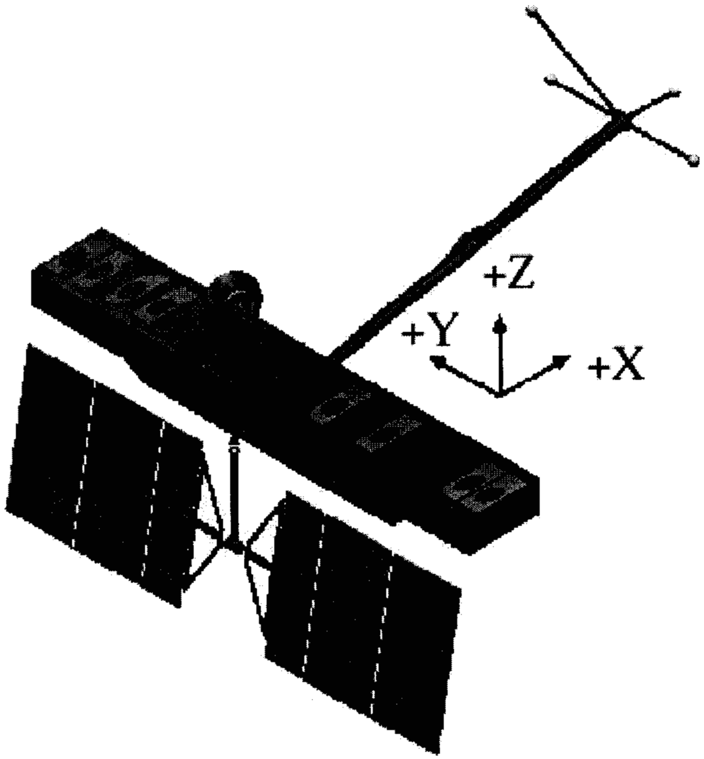


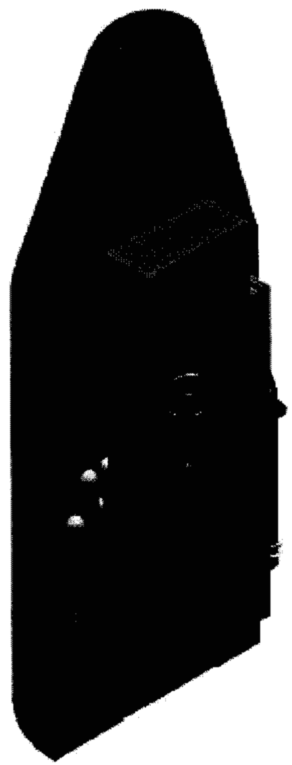
Space Interferometry Mission (SIM)

S I M



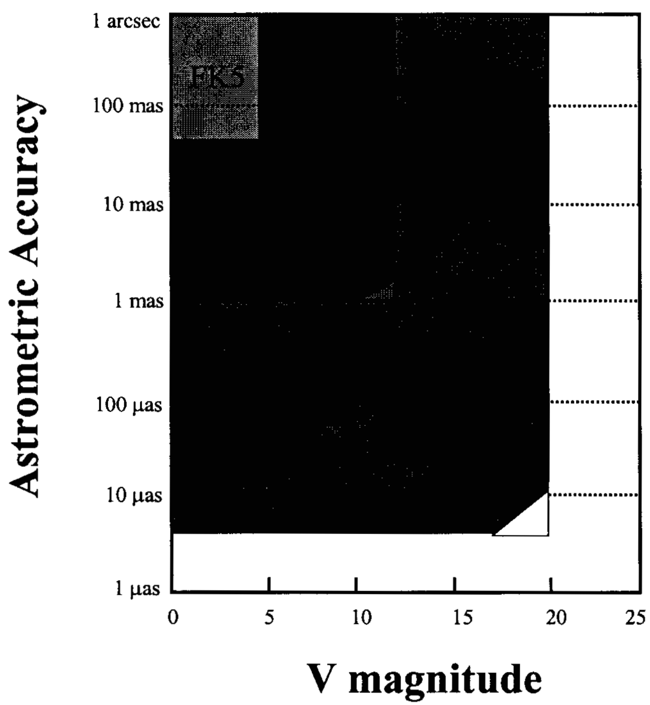
Space
Interferometry
Mission





SIM An Astrometric Mission

to Measure Positions of Stars with Extreme Accuracy

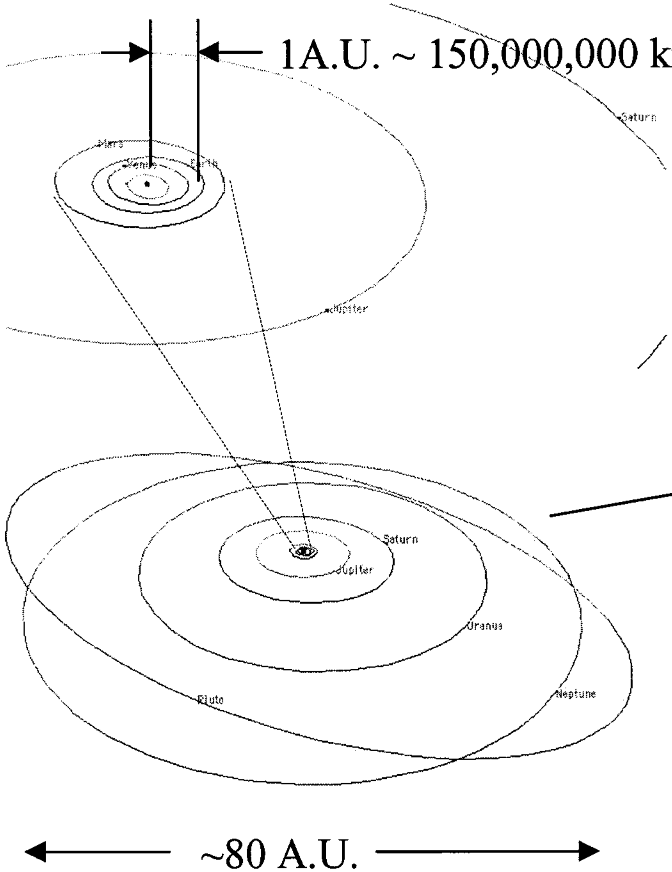


ExoPlanet Detection
Cosmic Distance Scale
Galactic rotation, Dark Matter

Demonstrate Starlight Nulling
with sub-nanometer stability
(for TPF mission)
Demonstrate synthetic aperture imaging

SIM extends the catalog
both in astrometric accuracy
and in star magnitude (faintness)

A Sense of Scale
Astrometric Planet Detection



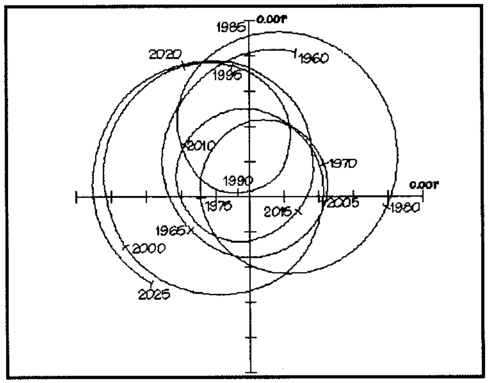
~400 stars
in the solar neighborhood
within 10 parsec
2 million A.U., 3×10^{14} km

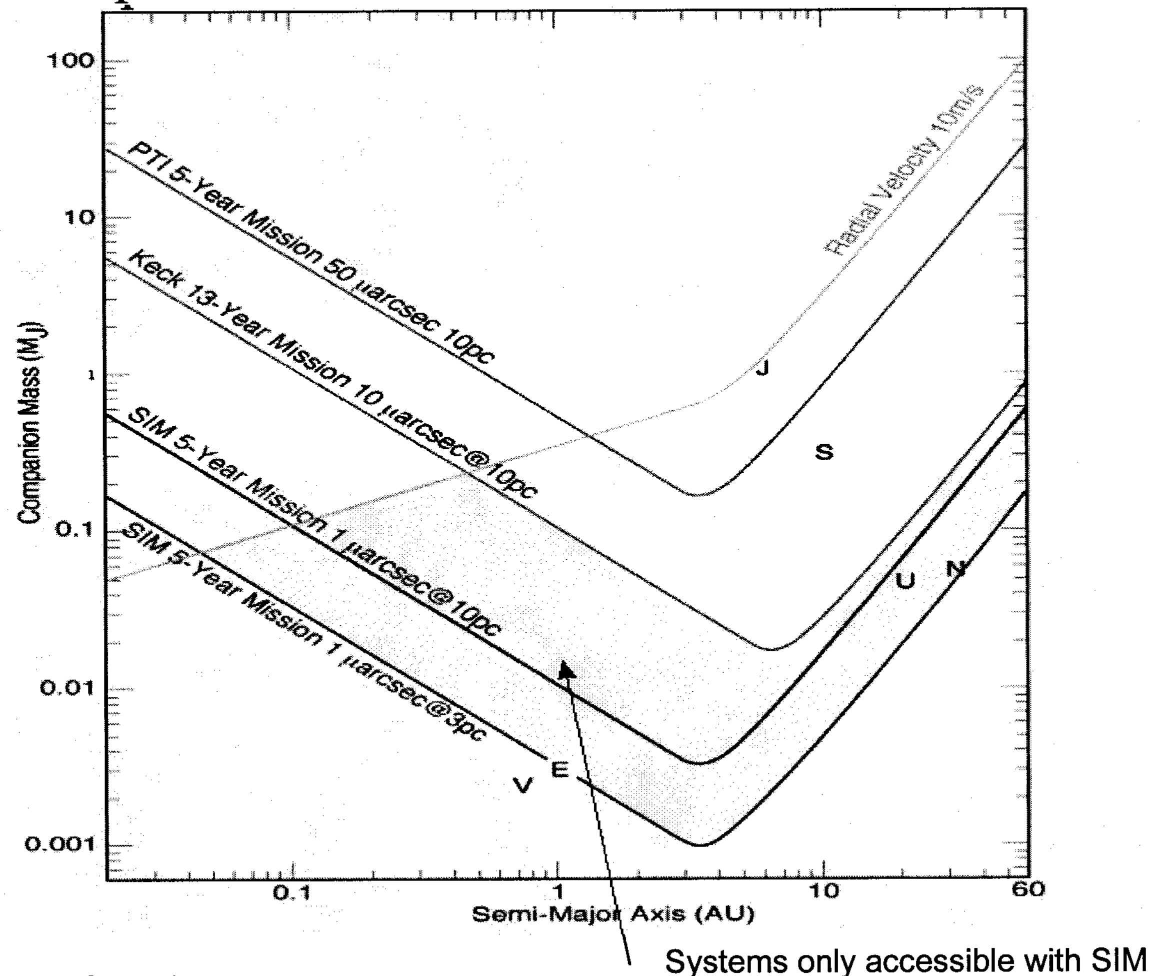
Nearest Stars a cen
~1.3 parsec
280,000 A.U.
42 trillion km

Sun's reflex motion (Jupiter) ~750,000km
Sun's motion from the Earth ~500km

Astrometric Planet Detection

Planetary systems inducing only low radial velocities (<~3m/s) in their central star that can't possible to detect from the ground can be detected through the astrometric displacement of the parent star.



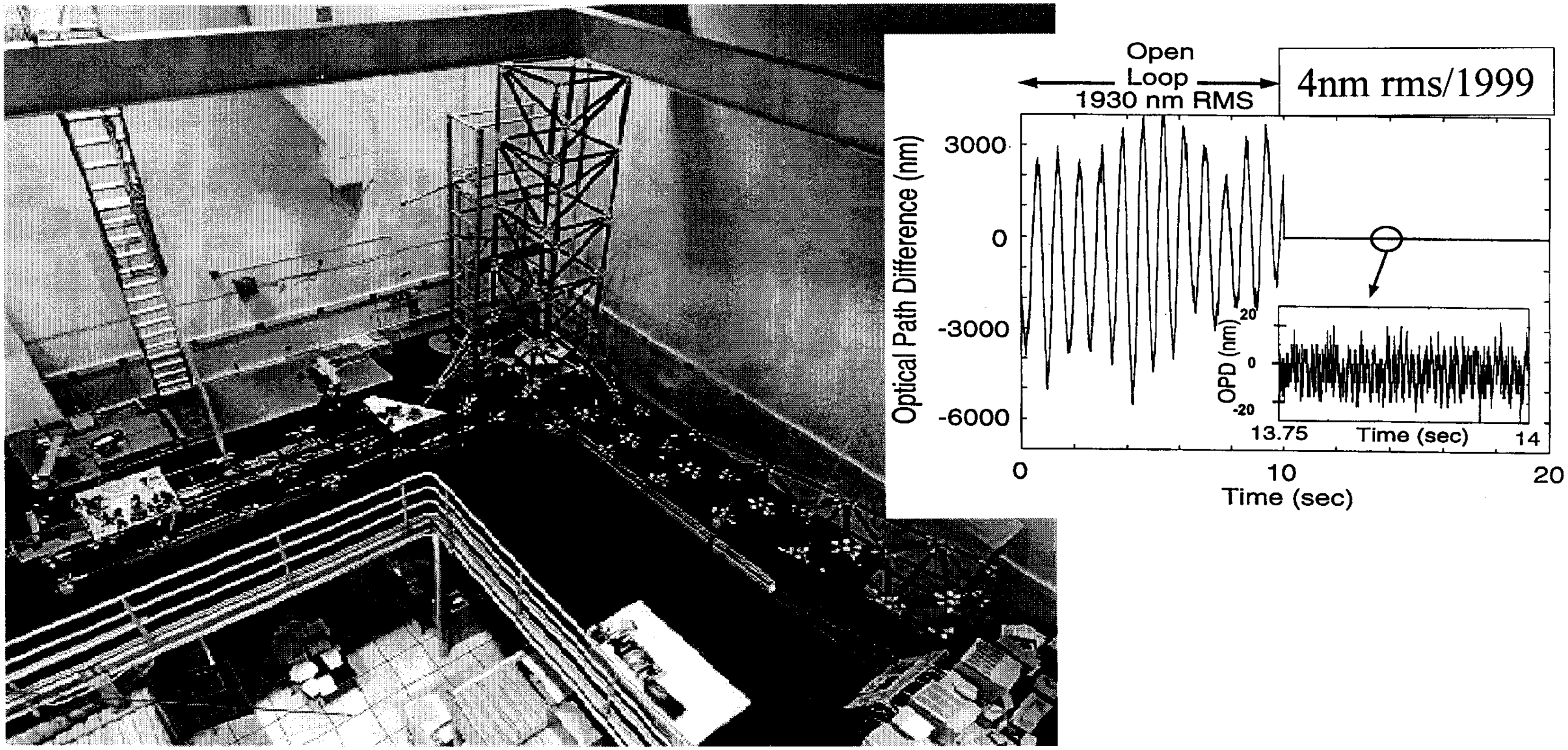


<u>Detection Limits</u>
SIM: 1 μas over 5 years (mission lifetime)
Keck Interferometer: 20 μas over 10 years

Technical Challenges

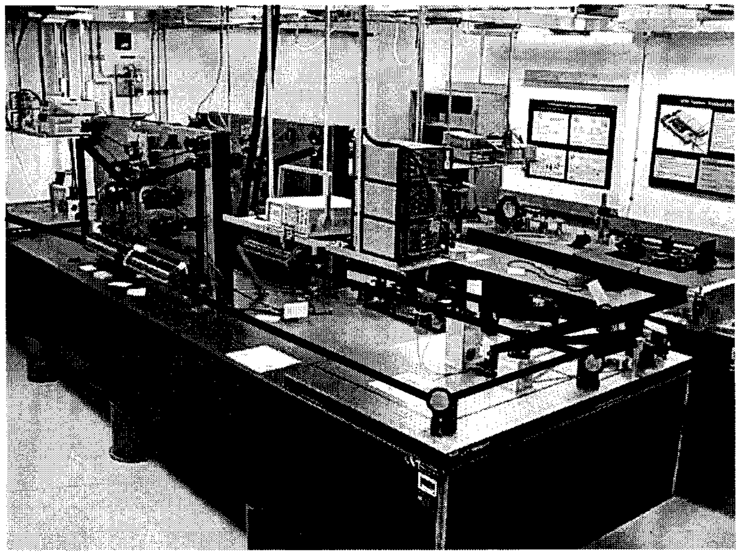
- Making a large (~12 meter) light weight/flimsy structure in space stable at the nanometer level (nano-technologies)
- Measuring the positions of the optical elements on SIM, with picometer accuracy to enable astrometry (positions of stars) at the ~1 uas (5 picoradian) level. (pico-technologies)
  - Detect a 2mm motion on the Moon, from Earth.
  - Goal is to detect the wobble of a ~3 earth mass planet around a star 10pc (30 lightyears) away.

Nanometer Control Testbed



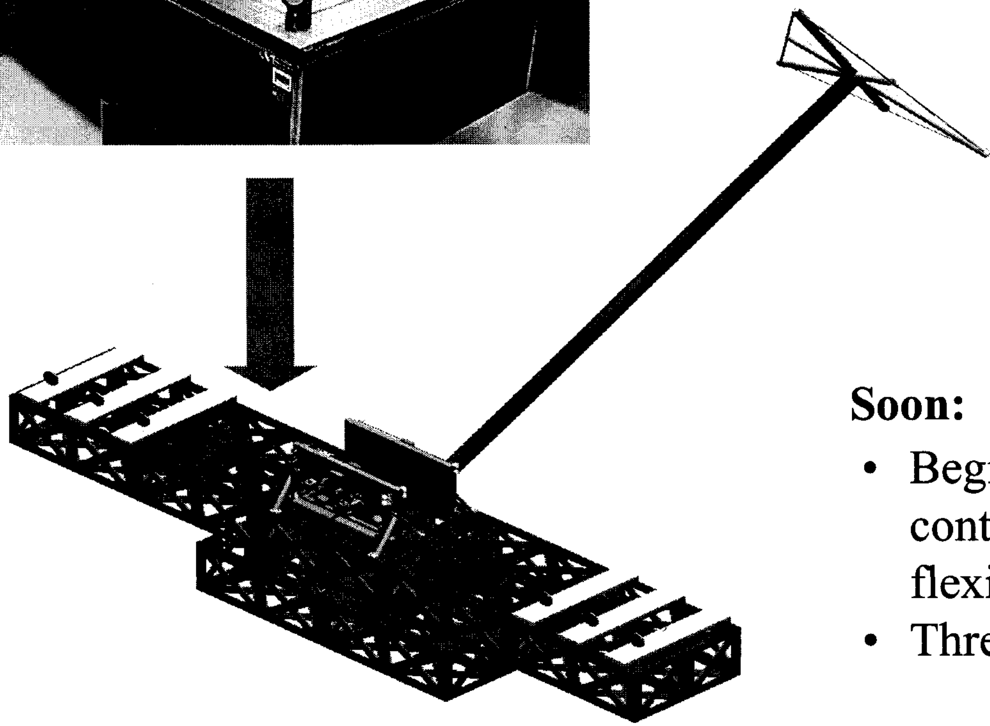
Flexible truss ~5 hz resonance
Simulated spacecraft disturbance (reaction wheels)
Active isolation of disturbance & active optical loop
(using laser interferometry as the sensor)

SIM System Testbed (STB-3)



Now: 3 baselines on optical table

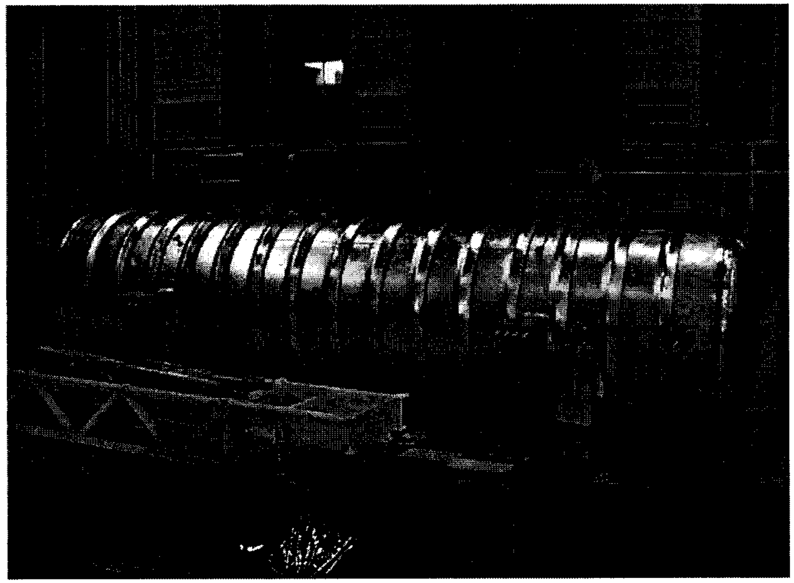
- Three interferometers now functioning on an optical table
- Completed detailed design of SIM-scale flexible structure to be built and installed by end-2000



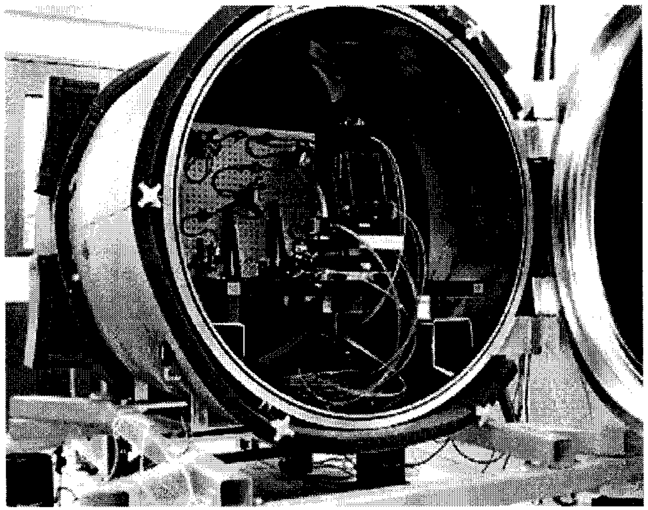
Soon: 3 baselines on structure

- Begin nanometer active control experiments on flexible structure
- Three baselines, full scale

Picometer measurement technology

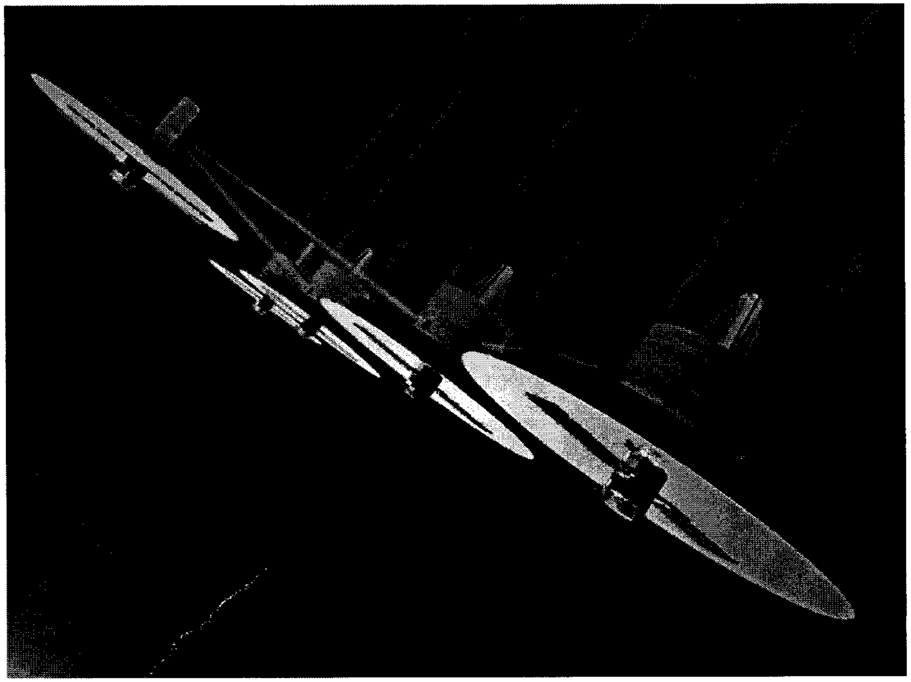


Component technologies
- *superprecise optical elements*
- *picometer laser gauges*
- *freq stabliized lasers*



Microarcsec Metrology Testbed
- *fully functional interferometer tested in vacuum at picometer levels*
- *verify testing procedure for flight hardware*

Terrestrial Planet Finder (TPF)



Direct Detection of Earth-like planets around nearby stars

Interferometric starlight nulling by ~ 10^6 to detect 10um (IR) light from the planet

~10 hrs of observation to detect an Earthlike planet @ 10pc

2~4 weeks to measure a low resolution spectra of the atmosphere, to identify H_2O, CO2, O3

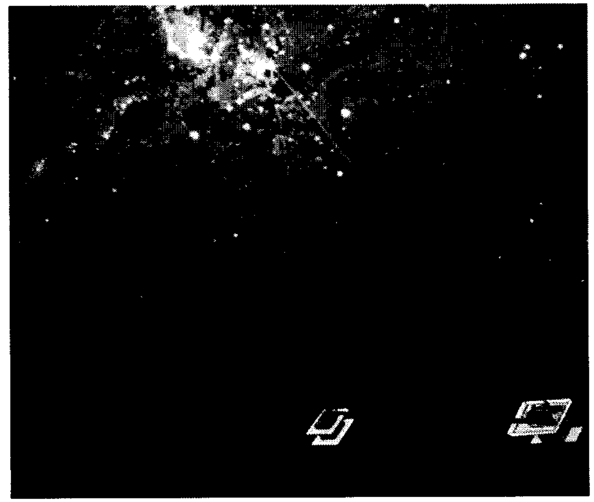
~4 large collecting apertures ~3m dia

Cryo optics (< 50K)

Separated spacecraft interferometry 50~500m

Pathlength control (nulling ~ 1nm)

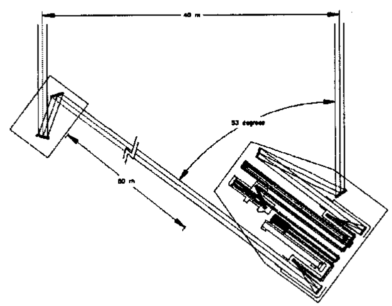
Multiple Spacecraft Interferometry ST-3 Technology Mission



- The New Millenium Program ST-3 Mission will provide validation of key enabling technologies for TPF when it flys in late 2003 including:
  - Separated S/C interferometry
  - Precision formation flying
  - Real-time optical control of a separated S/C interferometer
  - Angular and linear metrology
  - Inertial referencing for phasing and guiding
  - Separated S/C interferometer I&T techniques

DS3 2–SPACECRAFT INTERFEROMETER

Minimum baseline configuration for 20m fixed delay



Earths Around Other Stars?

Near term goals

Keck Interf Uranus/Neptue mass (outer planets)

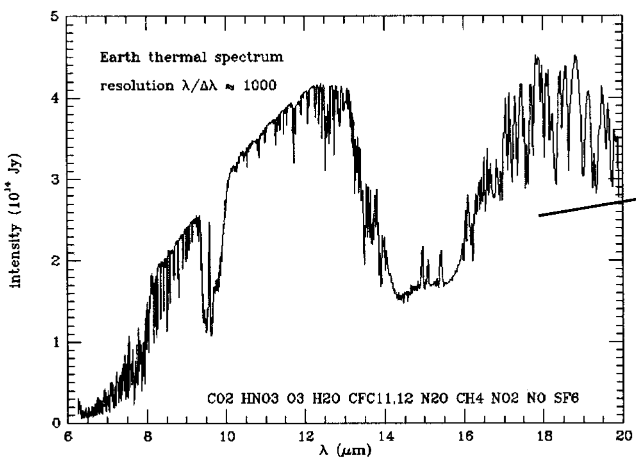
SIM Terrestrial Planets ~1 AU (few Earth masses)

Longer term goals

TPF IR detection of Earths, H2O, CO2, Oxygen

Detailed atmospheric studies of exo-Earth

(eventually images of oceans/continents)



Keck Interferometer Status